

Performance of MEMS-DCA SiC Pressure Transducers under Various Dynamic Conditions

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Abstract

We have characterized the static response of several SiC pressure transducers up to 400 °C and then tested them under two different dynamic conditions to determine the resonant frequencies and the effects of temperature. One of these dynamic tests was performed under a laboratory controlled shock tube test stand with an integrated oven, and another in a combustor test rig that simulated actual turbine engine conditions. In the shock tube test, the transducer was evaluated from 23°C to 400 °C and at 30 psi. The natural frequency of the transducers ranged between 290 and 340 kHz. The peak frequency did not shift for the entire range of temperatures, though the sensitivity dropped as the temperature increased. In the combustor test rig, the transducer was used to validate the existence of thermo-acoustic instability at 310 Hz operating at 420 °C and about 180 psia. These results provide further indication of the potential future insertion of SiC pressure transducers without complex packaging for applications in high temperature environments.

Key words: SiC Pressure Sensor, Dynamic Test, and High Temperature.

1.0 Introduction

Every transducer used in dynamic measurements needs to be characterized to ensure measurement accuracy. Dynamic pressure transducers are required to measure pressure fluctuations in the combustor chamber of jet and gas turbine engines. These fluctuations may indicate an onset of thermoacoustic instabilities that could degrade engine performance. Also, the demand for lower emissions (LE) in aircraft gas-turbine engines has resulted in advanced combustor designs that are critically dependent on lean-burning (LB) operation. However, LB/LE combustors are susceptible to thermo-acoustic instabilities that can produce large pressure oscillations within the combustor. This can at a minimum disrupt compressor flow or potentially lead to premature mechanical failures. A combustor is essentially an acoustic resonator. As an engine is run through its operating range, there are states where the heat release coupling with the acoustics forms unacceptably high pressure oscillations. Such instances have been well documented [1]. This problem is expected to be more pronounced in LB/LE combustion systems because less system damping is present with LB combustors due to reduced liner cooling. The reduced liner cooling is the result of the diversion of more cooling air to the combustion process. Traditionally this kind of

problem is resolved with pre-programmed open-loop FADEC adjustments; however, there is no guarantee that such techniques can deal with all of the instabilities. Previous works to study combustor thermo-acoustic instabilities have relied upon feedback signals from pressure sensors [2]. These either were cooled or were located at some stand-off distance from the combustor, which resulted in high background noise, transport delays, as well as frequency limitation. Optical sensors potentially can give faster, timely, and cleaner signals, but they would be more effective if they can resolve the events near the fuel injectors in the combustor front-end [3].

Furthermore, due to the high cost that is associated with the production of future engines, designers must have as much detailed information about the overall engine performance characteristics at high temperature as possible prior to its production. Such computer-based production thus relies heavily on computational fluid dynamics (CFD) codes that are used for the engine modeling, simulation, and the extraction of the optimum engine performance parameters before they can be manufactured. Therefore, it becomes of paramount importance that the accuracy and precision of these CFD codes are physically validated by experimental

results from engine tests with the utilization of robust instrumentation.

In this work, we first characterized the static pressure performance of MEMS Direct Chip Attach (DCA SiC pressure sensors at temperatures up to 400 °C in order to extract their operating parameters. This was followed by evaluation under two dynamic conditions, one being in a laboratory shock tube with an integrated high temperature oven, and the other a combustor test rig that simulates a real engine environment.

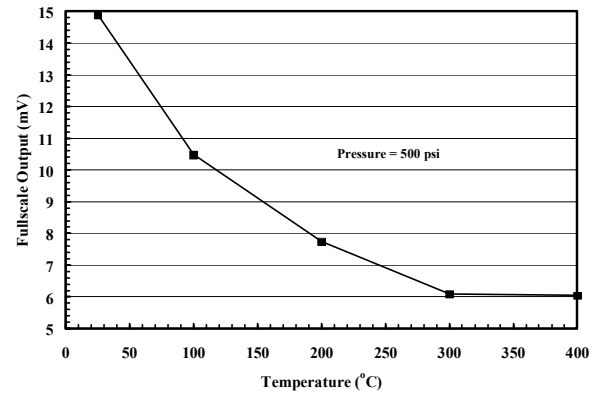
2.0 Transducer pre-test static calibration

For the purpose of pre-test calibration, a static characterization of the SiC pressure transducer is usually performed to extract calibration parameters such as the zero pressure offset voltage, V_{oz} , and full-scale output, V_{fso} . The transducers used in these tests were rated to operate up to 400 °C and 500 psi. The accelerated stress test (AST) protocol used for the static characterization has been reported elsewhere [4]. Briefly, the stability and reliability of SiC pressure transducer were evaluated at temperatures starting from 25 °C up to the temperature at which instability was observed. The result of the pre-test calibration in terms of the V_{fso} , and sensitivity after multiple thermal cycling is presented in Figs. 1a and b. The performance characteristics of the transducers depicted in the figures set the operational rating of the transducer. The parameterized characteristics shown in Figure 1 have been determined to be reproducible after the burn-in step of the AST as described in [4]. Therefore, they can be used for correcting the temperature induced deviations in the sensor output during data analysis. From Fig. 1a, it is seen that the $V_{fso}(P=500 \text{ psi}, T)$ becomes gradually smaller with increasing temperature. This behavior is characteristic of piezoresistive sensors commonly found in literature. The strain sensitivity at 400 °C, shown in Figure 1b indicates that the sensors still retain about 60% of its room temperature value.

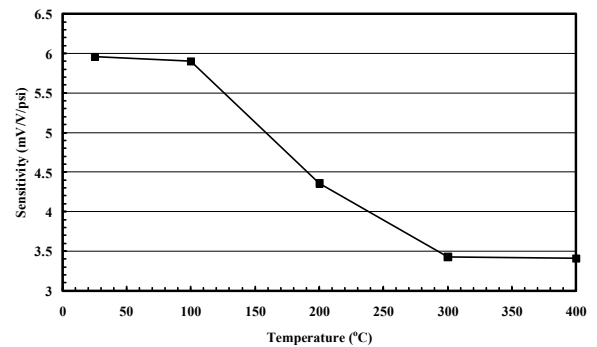
3.0 Shock tube test

The Wright State University (WSU) shock tube uses a two-chamber tube to propagate a normal shockwave that resembles a step input to a sensor. Figure 2 is a block diagram of the data flow. A thin membrane separates the two chambers, one chamber with high pressure and the other with atmospheric pressure. When the membrane is pierced, a series of pressure waves are produced that coalesce into a shockwave. The shockwave produces a step response, exciting the frequency spectrum of the transducer. Pressure at the transducer is determined from analytical normal shockwave theory. When using the sensor oven, the sensor is placed at the end

of the expansion tube in line with the stagnation path of the normal shock. The transducer being tested is located at the end of the expansion tube in the sensor oven. A battery is used to excite the transducer to isolate the signal from electronic noise that may be introduced by DC power electronics. The dynamic range of the transducers to be measured is greater than 100 kHz. The large bandwidth needed to accurately capture the dynamics of the system can be problematic. Use of a Tektronix differential amplifier capable of 1 MHz and with a selectable gain of 100 or greater, conditions the signal before digitization, giving adequate bandwidth. The computer is equipped with two DAQ cards, a high speed Gage Scope card capable of 5 Mhz and greater speed data acquisition and a National instruments brand card for controlling the high side pressure, measuring temperature, and actuating the plunger that breaks the membrane. Labview software is used to adjust settings, initialize the cards, and give feedback.



(a)



(b)

Figure 1: b) full-scale output at 500 psi of sic pressure transducer as function of temperature. The drop in output is due to decrease in strain sensitivity as shown in b.

A membrane of aluminum foil is used to separate the expansion and high side of the shock tube and a few

room temperature tests are done. The auto-spectral density is calculated from the transducer signal to see if the result is appropriate. If the results look reasonable the test is repeated several times to create an average for estimating the transfer function. This process is repeated for the desired temperature levels.

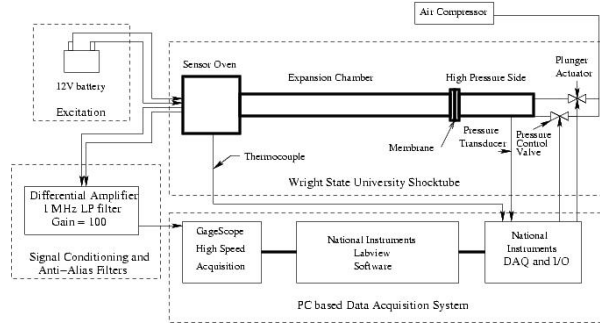


Figure 2: Diagram for heated sensor experimentation.

Each shock event needs to be windowed so that only the first shock is used in the calculations. Subsequent shocks are reflections inside the tube and have unknown excitations. The number of points used is a power of 2, convenient for using the Fast Fourier Transform (FFT). For data collected at 5 MHz the number of points taken is 2^{16} . An example of a windowed shock is shown in Figure 3. Another

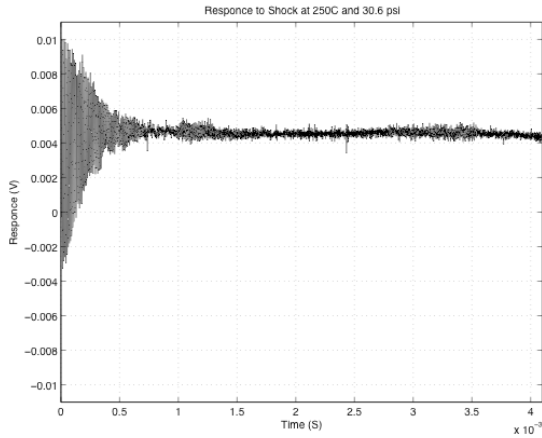


Figure 3: Time response of general sensor under test.

time history is produced representing a step response with magnitude equal to the pressure at the sensor (Figure 3). These time histories are then differentiated in the time domain. The data then represents the system response to an impulse rather than a step. The mathematics is the equivalent to taking the FFT first and then finding the H_0 transfer estimate. The benefit to taking the derivative in the time domain is the removal of DC drift observed from the same operation in the frequency domain, and being able to use common windowing techniques

like exponential. The H_v transfer estimate is then obtained using the time histories.

3.1 Shock tube results

The frequency and phase responses of the transducer as function of temperature are shown in Figure 4. The sensor seems to be very stable with a clean response through 100 °C. However, the peak slowly reduces in amplitude and the lower bandwidth response remains flat. At 150 °C the response peak widens and at 200 °C the response peak magnitude triples compared to the 24 °C data. The system peak reduces magnitude at 250 °C, but the lower bandwidth response is not flat. At 300 °C the system has a sharp peak with flat response. Both 350 °C and 400 °C have some variance in the lower bandwidth, with similar magnitude peaks. The peak frequency did not shift for the entire range of temperatures tested, though the sensitivity of the two transducers dropped as the temperature was increased. During the entire tests, the natural frequency of the sensor appears to be around 340 kHz.

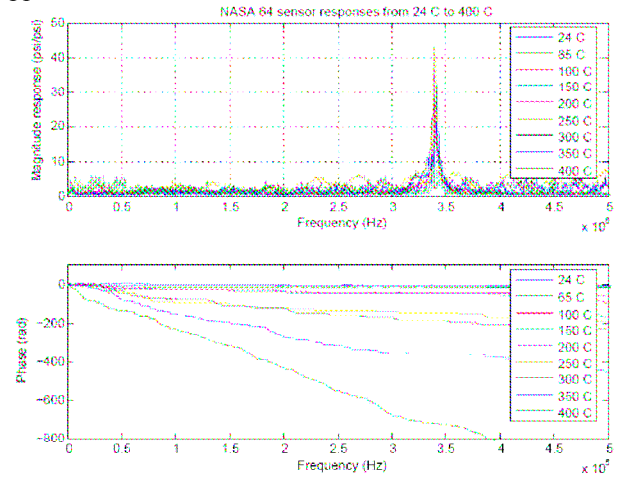


Figure 4: Frequency and phase response of SiC pressure transducer as function of temperature during shock tube test.

4.0 Combustor rig test

We utilized another un-cooled SiC pressure sensor to successfully demonstrate its survivability in the high temperature and high vibration engine environment. Combustion thermo-acoustic instabilities were measured at 420 °C and pressure up to 180 psi in an experimental test rig shown in Figure 4 [2]. The pressure transducer was then inserted and locked into a pressure port plug as shown in Figure 5. The ease of insertion into the combustor pressure port plug is due to the tubular design of the sensor sub-package that allows for flexible insertion into any

engine pressure port plug (e.g. a borescope plug) that can receive the package outer diameter of 0.25 in.

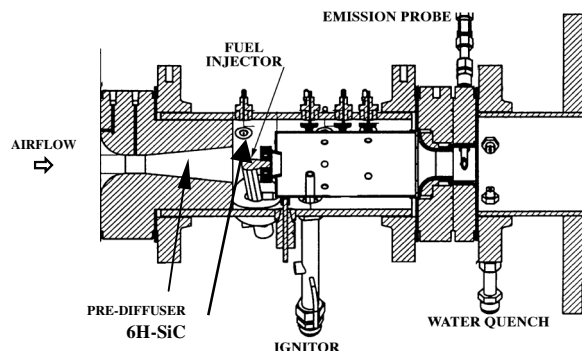


Figure 5: Test rig designed to replicate real instability at engine conditions. Location of the 6H-SiC pressure sensor relative to the combustion chamber is shown.

4.1 Combustor test results

Following the pre-test calibration, the SiC transducer was then inserted into the combustor test rig by screwing the pressure port plug, now with the sensor, into the location shown in Figure 5, where temperature could reach as high as 450 °C during operation. The response of the SiC pressure transducer (P3MEMS) was then compared with the facility reference transducer (P3) and a water-cooled

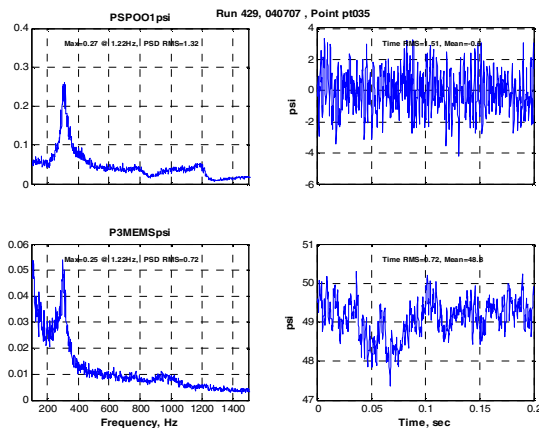


Figure 6: Amplitude spectral density (left column) and brief time history (right column) for the piezoelectric pressure transducer (PSP001) and the SiC pressure transducer (P3MEMS) shows the detection of thermo-acoustic instability at 310 Hz by both devices.

piezoceramic transducer (PSP001) that was located closest upstream in the rig. At ignition, at which the

highest temperature was recorded (420 °C), the SiC sensor strain sensitivity resulted in lower output relative to P3. However, the SiC output signal to noise ratio was sufficient to detect thermo-acoustic instability. Figure 6 compares the high frequency response of P3MEMS to PSP001 during the combustion process. The amplitude spectral density and brief time history from time of ignition shown in Figure 6 reveal the existence of thermo-acoustic instability at 310 Hz as detected by the P3MEMS. This was in excellent agreement with that obtained by the reference sensor PSP001.

5.0 Conclusion

The ability of un-cooled MEMS-DCA packaged SiC pressure transducers to be used for the sensing of dynamic pressure fluctuations in a combustion chamber has been demonstrated. The shock tube test indicated that the transducer has a high resonant frequency that is well above the frequencies that are associated with thermoacoustic instabilities in the combustion chamber of gas turbine or jet engines. The instability detected by the SiC was in excellent agreement with the one obtained by conventional water-cooled piezoceramic pressure transducers. Because this transducer is inserted directly into the sensed environment, real time accurate reading is obtained, thus leading to a more accurate validation of the CFD codes used for engine modeling.

6.0 Acknowledgements

This work was funded under the Propulsion-21 project managed by the NASA Ultra Efficient Engine Technology project. We thank the technical staff of the NASA Glenn Combustion Branch and Controls and Dynamics Branch for their support.

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IEEE Sensors Conference, Vienna, Austria,
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